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MEASUREMENT AND ANALYSIS OF THE MICROWAVE SURFACE RESISTANCE IN A MIXED PHASE Y-Ba-Cu-O SUPERCONDUCTOR

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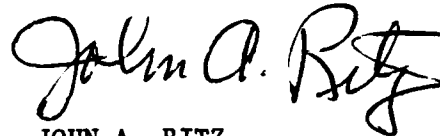RADC-TR-90-45 has been reviewed and is approved for publication.

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13. ABSTRACT (Maximum 200 words)

Absolute microwave surface resistance of a mixed-phased YBCO 88K superconductor has been measured at 16.5 GHz over the temperature range from 6 to 90K. The data revealed at least 2 superconducting phases. A phase with lower transition temperature produces a residual surface resistance marked by a discontinuity in surface resistance versus temperature at 52K. This phase is apparently closely related to the "60K bulk" YBCO superconductor. An additional resistance discontinuity occurs at 83K. Microwave surface resistance is thus a diagnostic tool for multiphase superconductors. With recognition that mixed superconducting phases act as added residual resistances, the Mattis-Bardeen theory gives a good fit to the superconducting surface resistance for both phases.

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Preface

We would like to acknowledge the fine help given us by John Steinbeck, Boris Tomasic, Hans Steyskal, Jim Sethares, George Roberts and Jose Silva.

Measurement and Analysis of the Microwave Surface Resistance in a Mixed Phase Y-Ba-Cu-O Superconductor

Important applications for the new classes of high temperature superconductors may occur in the microwave region. These new superconductors include Y-Ba-Cu-O (YBCO), Bi-Ca-Sr-Cu-O and Tl-Ca-Ba-Cu-O with nominal superconducting transitions near 90, 110 and 125K, respectively. With low cost liquid nitrogen cooling, these new superconductors promise economically feasible microwave circuits with lower resistive loss, higher Q, lower noise, and wider bandwidth than is found with conventional microwave conductors.[1,2] How well this promise is kept depends on the real microwave characteristics of these materials.[3,4] This paper presents data and analysis on the absolute microwave surface resistance at 16.5GHz of the very common superconductor YBCO, in pressed bulk ceramic form, over the temperature range from about 6 to 90K.

[1]   Carr, P.H. (1987) Potential microwave applications of high temperature superconductors *Microwave Journal*, **30**(6):91.

[2]   Carr, P.H. and Derov, J.S. (1988) High temperature superconductors and their promise for better microwave circuits, Inv. Paper, Frequency Control Symposium.

[3]   Martens, J.S and Beyer, J.B. (1988) Microwave surface resistance of YBaCuO super-conducting films, *Appl. Phys. Lett.* **52**:1822.

[4]   Dykaar, D.D., Sobolewski, R., Chwalek, J.M., Whitaker, J.F., Tsiang, T.Y., and Mourou, G.A. (1988) Superconducting transmission lines, *Appl. Phyus. Lett.* **52**:1444.

The surface resistance R of a superconductor vanishes for dc but not at high frequencies. At a fixed frequency ω in a single phase superconductor, a common empirical observation[5,6] is $R(T,\omega) = R_o(\omega) + Rs(T,\omega)$, where $R_o(\omega)$ represents a residual contribution to the surface resistance and $Rs(T,\omega)$ represents the superconducting contribution to the resistance. Ideally, $Rs(T,\omega)$ vanishes at T = 0K for frequencies whose photon energy is below the superconducting gap $\hbar\omega << E_g = 3.5$ kBTc while $R_o(\omega)$ does not vanish at zero temperature. The nature of the residual resistance is presumably due to impurities[5], surface imperfections[6] and pinned magnetic flux.[5,7] In the YBCO ceramics, grain boundaries[8] and spatial variations in stoichiometry contribute to the high surface values measured to date. Our results show that our ceramic sample forms a mixed phase superconductor. The presence of a superconducting phase of lower transition temperature (~52K) contributes a separate resistance which decreases rapidly as the temperature drops below that phase's superconducting transition. Thus, in addition to defining the utility of superconducting materials for microwave applications, microwave measurements serve as a very useful diagnostic tool in identifying the presence of lower transition temperature phases in superconductors which are undetectable using dc techniques.

The YBCO ceramic sample was prepared from reacted oxide powders. The mixture was cold pressed and then sintered to 920-940C for 12 hours. The surface resistance of the ceramic YBCO disc was determined by measuring the quality factor Q of a 16.5 GHz brass cylindrical cavity operating in the TE (011) mode[9,10,11,12] with the sample disc used as one end wall. The cavity with YBCO sample was inserted into a 2 inch cylindrical tube, evacuated for 30-60 minutes to remove any water vapor, and then inserted into a liquid helium dewar. The temperature was monitored as the system slowly warmed from 6 to 100K.

At each temperature a network analyzer[9] measured the ratio of reflected to incident power. At resonance the reflected power is a minimum and the absorbed power is a maximum. The loaded cavity Q was determined using the resonant frequency and the half power points. The

[5] Van Duzer, T. and Turner, C.W. (1981) *Principles and Properties of Superconductive Devices and Circuits*, Elsevier, New York .

[6] Gittleman, J.I. and Rosenblum, B. (1964) Microwave properties of superconductors, *Proc. IEEE* **52**:113.

[7] Allen, L.H., Beasley, M.R., Ammond, R.H., and Turneaure, J.P. (1983) RF surface resistance of high-T_c superconducting A15 thin films. *IEEE Trans MAG* **19**:1003.

[8] Hylton, T.L., Kapitulnik, A., Beasley, M.R., Carini, J.P., Drabeck, L., and Gruner, G. (1988) Weakly coupled grain, model of high-frequency losses in high T_c superconducting films, *Appl. Phys. Lett.* **53**:1343-1345.

[9] An S-parameter test set, HP-8620C sweep oscillator and HP-8409 network analyzer were operated through a HP-9826 controller. Temperature was monitored with a Lake Shore Cryotronics CGR-1500 carbon glass resistor and Keithly 196 digital multimeter.

[10] Sucher, M. and Fox, J. (1963) *Handbook of Microwave Measurements*, Vol. II, Chapt. VIII, Polytechnic Press.

[11] Ginzton, E.L. (1957) *Microwave Measurements*, Chapt. 9, McGraw-Hill.

[12] Maxwell, E. (1964) *Progress in Cryogenics*, Vol. 4, pp. 123-158, Academic Press.

unloaded Q was calculated from the value of the reflection coefficient at resonance with the known cavity coupling. The coupling loss was neglected in calculating the unloaded Q. The surface resistance[13] was obtained by

$$Q = \frac{\omega_0 \mu}{2R_s} \frac{\int |H|^2 \, dV}{\int |\hat{n} \times H|^2 \, dS_{side} + 2\int |\hat{n} \times H|^2 \, dS_{end}} \quad . \tag{1}$$

The degeneracy between TE (011) and TM (111) modes was removed by use of a coupling loop and by cutting a groove in the cavity wall.[14] The experimental arrangement was initially tested using the plain brass cavity to determine the surface resistance of the metal

The absolute surface resistance (with error limits) of the YBCO ceramic is given in Figure 1. There is an initial rapid drop in the surface resistance as the temperature drops below about 88K in the superconductor, a leveling off and then a second, very rapid decrease below about 52K. Finally the surface resistance, 0.033 ohm, levels to a temperature independent residual below 30K. This is about 2 times the surface resistance of copper.

[13] Jackson, J.D. (1975) *Classical Electrodynamics*, 2nd ed., Chapt. 8, John Wiley & Son, New York.

[14] Collin, R.E. (1966) *Foundation for Microwave Engineering*, McGraw-Hill, pp. 336.
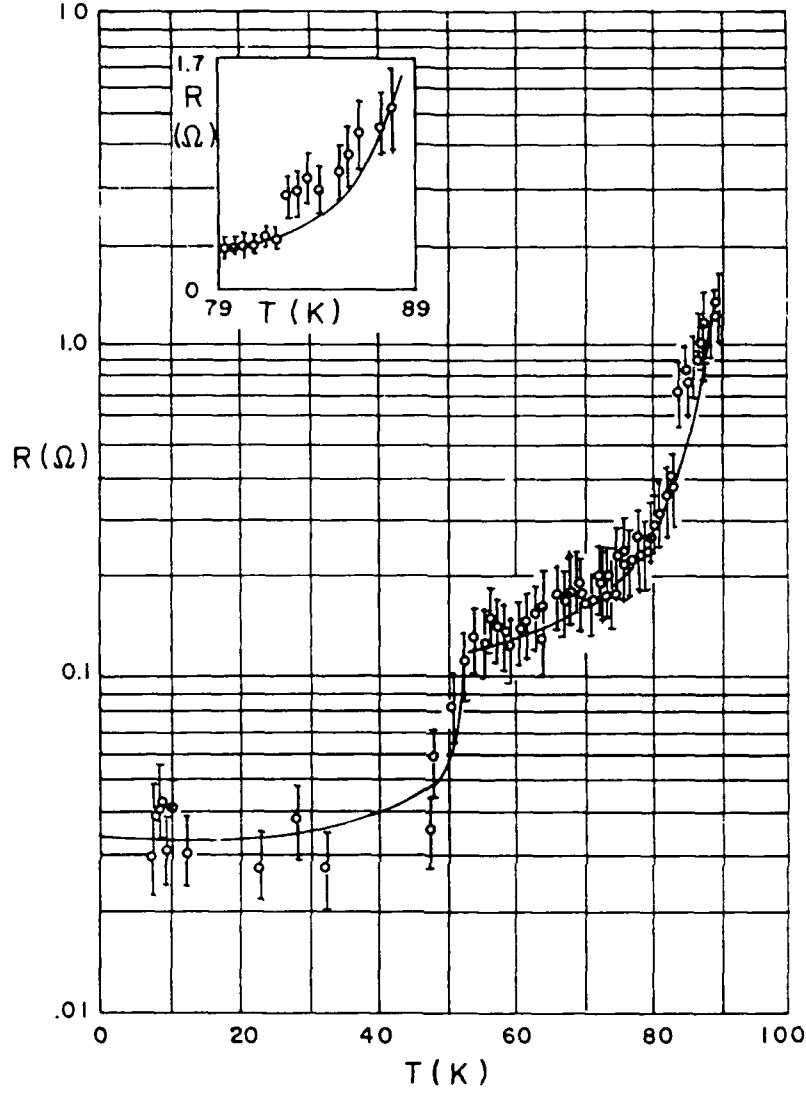
Figure 1. YBCO Surface Resistance at 16.5 GHz. Temperatures are accurate within ± 1K over the region where the data points are dense. The solid lines present the theoretical results. Parameters used in the theoretical fitting are R_o = 0.033Ω, R_{n1} = 1.5Ω, R_n = 0.7Ω, S_1 = 5, and S_2 = 1. R_{n1} and R_{n2} are the normal resistance values for the 90K and 60K phase transition respectively and S is the coherence parameter $1k_BT_c/hv_F$. The inset shows the surface resistance above 79K on a linear scale. The surface resistance drops to almost 1/2 its value within a half degree.

The initial leveling of surface resistance above 52K suggests the presence of a middle temperature residual resistance and the sharp drop in surface resistance below about 52K clearly identifies this middle temperature "residual" resistance as a superconducting phase of YBCO. A "60-K bulk superconductor" has been identified[15] in polycrystalline $YBa_2Cu_3O_{7-y}$ as a oxygen deficient phase with a value of y near 0.33. When y is near zero the high temperature phase of YBCO occurs with a transition near 90K.

In view of the clear correlation of the sharp discontinuity in the data between 50-K and 60-K with the nominal 60-K bulk superconducting phase, we have analyzed the surface resistance of our pressed ceramic using the formula $R = R_o + R_{s1}(T) + R_{s2}(T)$. This formula generalizes the well-established additive property of a single residual resistance to several residual components. Here R_{s1} and R_{s2} represent contributions to the surface resistance due to the higher temperature superconducting phase at 88K and a lower temperature superconducting phase at 52K while R_o is the usual residual resistance.

We fit the surface resistance data over our temperature range with the theoretical surface resistance in the local limit derived by Sang Boo Nam[16] (Nam) from Mattis-Bardeen[17] theory. The Mattis-Bardeen theory is soundly based on first principles and has been well tested with conventional superconductors.[18] The local limit requires that the mean free path is much smaller than the London penetration depth and is an excellent approximation for the high temperature superconductors. The surface resistance was also computed at several temperatures using the full Mattis-Bardeen theory as formulated by Turneaure[18] in his thesis. A comparison between surface resistance calculation in the Nam limit, which requires only single numerical integration, with the Turneaure formulation, which requires double integration, showed excellent agreement between the two methods in the range of parameters applicable to high temperature superconductors in general and our sample in particular. An alternative method of analysis is the semi-empirical two-fluid model which is quite simple but unfortunately deviates considerably from Mattis-Bardeen theory.

The Nam version was programmed to give Rs(T)/Rn as a function of scaled temperature and a coherence parameter $S=lk_BTc/h \, v_F$ where l is an effective mean free path and v_F is the Fermi velocity. The anisotropic high temperature superconductor resistance was normalized to its normal state resistance and then fit to the Mattis-Bardeen theory. Though Mattis-Bardeen theory is for isotropic materials, the high temperature superconducting materials show the same functional behavior. The solid curve in Figure 1 is the Mattis-Bardeen-Nam calculation for our material using transition temperatures of 88 and 52K for the two superconducting

[15] Cava, R.J., Batlogg, B., Chen, C.H., Rietman, E.A., Zahurak, S.M., and Werder, D. (1987) Single-phase 60-K bulk superconductor in $Ba_2YCu_3O_{7-8}$ (0.3 < & < 0.4) with correlated oxygen vacancies in Cu-O chains, *Phys. Rev. B* **36**:5719.

[16] Sang, Boo Nam 1967) Theory of electromagnetic properties of superconductors and normal systems I, *Phys. Rev.* **152**:(No. 2):470-486.

[17] Mattis, D.C. and Bardeen, J. (1958) Theory of anomalous skin effects of super-conductors, *Phys. Rev.* **111**:412.

[18] Turneaure, J.P. (1967) *Microwave Measurements of the Surface Impedance of Super-conducting Tin and Lead*, Ph.D. Thesis, Stanford University, HEPL Technical Report No. 57.

phases. The Turneaure formulation will give essentially the same theoretical curve. The values of R_o, Rnl and Rn2 were taken as 0.033, 1.5 and 0.07 ohm, respectively. The value S1 was 5 while S2 for the 52K phase material was 1.

The 88K normal surface resistance can be used to estimate the resistivity ρ of our non-superconducting material through the standard formula Rn = $(\mu\omega\rho/2)1/2$ (MKS) with μ and ω the permeability of free space and the frequency respectively. Our value of 1.5 ohm for Rnl yields a resistivity of 3.5 ± 0.7 ohm-cm which falls nicely within the resistivity range found in Reference 8 for their 90K superconducting phase and by other investigators for polycrystalline YBCO. Inspection of the data shows that an additional superconducting phase is probable at 83 ± 1K[19] and may coincide with the YBCO structure found near 85K (T/Tc = 0.92) in Reference 9. Similar structure has been found near the upper temperature transition in A 15 superconductors.[7]

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[19] Berkley, D.D., Kim, D.H., Johnson, B.R., Goldman, A.M., Mecartney, M.L., Beauchamps, K., and Maps, M.L. (1988) Presentation of Y2Ba4Cu8020-x thin film by thermal co-evaporation, *Appl. Phys. Lett.* **58**:708-709.

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4. Dykaar, D.D., Sobolewski, R., Chwalek, J.M., Whitaker, J.F., Tslang, T.Y., and Mourou, G.A. (1988) Superconducting transmission lines, *Appl. Phyus. Lett.* **52**:1444.

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15. Cava, R.J., Batlogg, B., Chen, C.H., Rietman, E.A., Zahurak, S.M., and Werder, D. (1987) Single-phase 60 K bulk superconductor in $Ba_2YCu_3O_{7-8}$ ($0.3 < \& < 0.4$) with correlated oxygen vacancies in Cu-O chains, *Phys. Rev. B* **36**:5719.

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